Report to NASA on a Workshop on Sea Ice Data Assimilation

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Report Edited by
Kim Partington, Ronald Lindsay, Jinro Ukita

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1 Executive Summary

NASA's Earth Science Enterprise (ESE) aims to understand the Earth system including the effects of humans on the environment. The value of data assimilation (DA) to operational weather forecasting is well recognized, but it has only been comparatively recently that its application to climate research has been initiated. Within this context, a number of DA projects with specific application to sea ice are now under way. This workshop on sea ice DA was organized to assess overall progress made by these projects and to help to address recommendations in a joint effort to enhance the productivity of this area of research.

The workshop objectives, key strategic areas, priority recommendations, and metrics are summarized below. This is followed by background section. The main body of this report consists of three sections: issues and strategies, recommendations and metrics. Information on the agenda of the meeting, the list of attendees and the summary of presentations may be found in the appendices.

The following objectives were set out for this meeting:

- To provide recommendations to NASA on how to improve the collective productivity of data assimilation projects both current and future, including:
  - Collaborations and links between projects and expert groups
  - Generic and specific improvements to NASA datasets
- To generate informal links between related projects that can help to address the complexities of data assimilation. This community is one in which mutual support may be particularly useful given that that the projects are pilot projects.
- To agree on the key technical issues that need to be addressed to make progress with data assimilation. In particular, to agree on a consensus approach, if appropriate (building on, or modifying the approach recommended by NSIDC at their workshop as reported in Weaver et al., 2000).
- To consider how progress may be assessed with data assimilation: milestones, evaluation criteria, and priorities.

In order to build sound strategies the workshop identified five essential areas in the DA procedures as:

- Formulating science questions to be answered,
- Preparation for assimilation
  - Selecting and constructing a model and DA methods and determining their error charateristics,
  - Selecting forcing and assimilation data and determining their errors,
- Performing model simulations with DA, and
- Evaluating the model results with respect to the questions posed.

The recommendations arising from the meeting were as follows:

Science questions

- NASA should ensure that the sea ice community generates a consensus view on any unique role of DA in addressing NASA's science questions and ensure that the key questions are publicized among the research community. A starting point is provided in this document.
- NASA should ensure that the community regularly updates its estimates of required accuracies of parameters to address the science questions, and that investigators are aware of where these NASA-approved estimates can be found. These can be used to guide the practitioners of DA.

Scientific Community Outreach

- NASA should support the availability of a web-based or other tutorial for data assimilation aimed not at fellow experts in the field, but at scientists and graduate students who would like to become proficient practitioners of the art. A summer school in DA would also be of benefit to encourage a new generation of expertise in DA among the sea ice community.

Models and DA methods

- Model tuning as a "zeroth" order DA activity should be routinely carried out by modelers. The tuning should be systematic, documented, and repeatable since it can change if any of the model parameterizations or the forcing functions are changed. Strategies for the use of DA in model tuning need to be considered carefully, possibly within the framework of coordinated model tuning activities using similar domains.
- NASA should ask for model results to be accompanied by estimates of the model error covariance, which likely vary in time and space.
- NASA should support a very simple sea ice adjoint model so that we can gain experience in this type of model. The strategy here is to start simple rather than to attempt to construct an adjoint model from a fully complex thickness-distribution model. This should be complementary to other supported studies that are based on simpler DA methods such as Optimal Interpolation, which has been found to be effective in improving the calculation of both ice motion and thickness.

Selecting forcing and assimilation data

- Encourage data providers to characterize the error covariance of both forcing and assimilation data. It is important to understand any covariability in the errors, since the errors are often not independent and the covariance is needed for proper data assimilation.
- Encourage modelers to
    - identify accuracy requirements for data providers in order to be able to answer the science questions under investigation.
    - specify data formats that are most useful.
- NASA should support development of improved data products, including:

- snow depth. The depth on refrozen leads and thick ice may be quite different, a difference that is important for growth rate calculations.
- ice thickness.
- a single archive of ice thickness measurements from submarines and moorings.
- better characterization of the errors in SSMI-based ice concentration estimates.
- lead-fraction data sets.

➢ NASA should consider support of studies that test assimilation scenarios involving pre-satellite era sea ice data as well as post-satellite era sea ice data.

Assimilation stage

➢ NASA should make available to individual investigators computational resources that could be accessed quickly for short time periods, say six months, until more long-term support could be obtained. The resources should include access to popular modeling environments, such as Matlab or IDL, and sufficient disk space to keep large model outputs. Community-wide DA programs should also be considered as a means of obtaining good return on investment in DA.

Evaluation stage

➢ DA investigators should clearly establish whether their accuracies are most limited by the DA method, the data or the model, or some combination.

➢ All studies should go beyond quantitative evaluation of the results of DA and should consider the implications for future observation requirements as well as model improvements.

The meeting attendees also considered how NASA might evaluate progress in data assimilation applied to sea ice research questions, and review the overall value of this area to its research objectives. The following so-called “metrics” were proposed.

By Project:

(a) Does the project clearly address one or more science questions?
(b) Does the project address a temporal and spatial domain appropriate for the science questions, and does the project select parameters, establish error requirements and prepare a model and method all in a self-consistent manner? Mismatch between the DA method, the science questions being addressed, and the knowledge of errors in the data, for example, needs to be avoided.
(c) Does the project result in a quantitative evaluation of the results of DA?
(d) Does the project result in recommendations to NASA relating to datasets and model improvements?

By Community:

(a) Has the sea ice community identified a set of specific science questions that are particularly geared toward and/or suitable for DA? Has the particular role of DA in answering NASA’s Earth Science Enterprise science questions been established?

(b) Are there any significant gaps in the current range of science questions being addressed with DA, based on those questions identified as being most appropriate for DA in (a)?

(c) Has a consensus methodology been established for evaluating the results of DA?

(d) Does the sea ice DA community have the combined expertise and means of communication to build up the critical mass necessary to carry out an effective program of DA for sea ice, in particular to address activities such as a development of a community adjoint model or broadly-accepted recommendations on data acquisition?

2 Background

NASA's Earth Science Enterprise focuses its research around key science questions that involve the identification and understanding of changes in the Earth environment and ultimately relate to our collective well-being. Within the Earth environment, sea ice acts as an interface between the ocean and the atmosphere, and has a significant control on the way in which the energy and material are transferred within the Earth climate system. The potential for any significant climate change, specifically that with an anthropogenic origin, is dependent on the nature of this control. Evidence suggests that changes are taking place in sea ice cover particularly in the Northern Hemisphere (Parkinson *et al*., 1999; Rothrock *et al*., 1999). This is in addition to growing evidence, through simulations by global circulation models, suggesting that reductions in sea ice coverage may amplify climate change. However, there remain disagreements between models regarding the magnitude of this amplification, which are to a significant extent attributed in varying degrees to representations of the polar, particularly sea ice, processes by these models. NASA's research program therefore includes studies aimed at understanding the role of sea ice within the Earth climate system and assessing the extent to which sea ice may be a source of amplified change involving such processes as thermohaline circulation and ice-temperature feedbacks.

With a range of predictions and sparse observations for the state of sea ice cover, the challenge lies in making highly efficient *combined* use of data and model outputs in order to minimize errors and uncertainties and thus to obtain the best possible picture of what has happened and is now happening at high latitudes. Observations allow us to identify past behavior of the climate system and to verify models, while models allow us to understand the observed behavior and make predictions. Data assimilation provides a consistent conceptual and analytical framework in which models and observations are used so as to maximize their joint strengths in a rational and quantitative manner. It also forces a dialogue between modelers and observationalists, points to where the main sources of errors lie, allows optimal estimation of unobserved parameters such as ice thickness, and helps to assess where new datasets would be most beneficial.

Although the arguments for pursuing data assimilation in the context of sea ice research are persuasive, progress has been relatively slow in exploiting this technology for the following reasons.

- The DA techniques can be conceptually complex and computationally demanding, and lie outside traditional areas of expertise of sea ice researchers.
- Their use involves investment of time in developing the necessary skills to prepare credible proposals, or in unfamiliar partnering with appropriate expertise from outside the sea ice arena.
- Sea ice datasets and models have not, in most cases, been designed with data assimilation in mind and so are not convenient for data assimilation. In many cases, the errors are not well characterized.

The temptation is therefore to make use of unrealistic assumptions about errors in order to implement data assimilation, or to invest considerable effort in understanding the errors as a precursor to addressing any science with data assimilation. Neither approach is likely to find it easy to attract funding.

The advantages on the other hand include:

- The accumulation of experience and skills in the assimilation of weather data for numerical forecasting, as long as this experience can be effectively transferred to the sea ice community.
- Numerous forward modeling activities that, in the past, have formed the basis for inversion algorithms and could be applied to data assimilation.
- A recent large increase in the range of datasets available to the polar research community, such as ice motion from a variety of sources (Emery *et al*., 1997) and new microwave data from sensors on NASA's AQUA mission.
- A large increase, over the last decade or so, in the number and capabilities of coupled ice-ocean models involving increasingly sophisticated ice rheologies and improved resolutions.

In 1997, the National Snow and Ice Data Center (NSIDC), with NASA support, sponsored a workshop whose goal was to explore issues involved in applying data assimilation to sea ice research (Weaver et al., 2000). This stimulated debate and resulted in a set of recommendations as summarized below:

- Use simple data assimilation models in pilot studies.
- Take an incremental approach to the development of DA program as follows.
    - Use low resolution models first to determine whether improvements can be gained in sea ice parameterizations, then move onto higher resolution models involving higher frequency behavior and multiple variables.
    - Couple radiative transfer models to ice models to explore the value of the forward modeling approach
- Investigate coupling of activities between the operational and academic research communities.
- Data providers should generate error statistics with their products and pixel time tags. An initial prime candidate is a passive microwave orbit-based dataset.
- Reconfigure datasets to provide data at a temporal resolution of higher than 1-3 day sampling.

In part responding to NSIDC's recommendations, but in large part motivated by a clear need recognized within NASA's Earth Science Enterprise, NASA's Cryospheric Program responded by calling for some pilot studies and directed some funding towards a series of pilot data assimilation studies, mainly through the NASA Research Announcement NRA-00-OES-05 on "Oceanography" (Table 1, see below).

Table 1. NASA-supported sea ice data assimilation projects (as of August 2002)

Arbetter, Todd	University of Colorado	*Investigation of the Assimilation of Ice Motion Data in Sea Ice Models*
Holland, David	New York University	*Ice-Shelf Ocean Interactions Along the Western Antarctic Peninsula: A Synthesis Using a Coupled Sea-Ice-Ice Shelf-Ocean Model, Satellite Radar Interferometry, and Autosub Hydrographic Data*
Kwok, Ronald	Jet Propulsion Laboratory	*Testing Sea Ice Models with RGPS Data and the Momentum Balance*
Lindsay, Ronald	University of Washington	*Lagrangian Assimilation of Satellite Data for Climate Studies in the Arctic*
Liu, Antony	Goddard Space Flight Center	*Optimization of Sea Ice Model for Ice Deformation and Visco-Plastic Rheology Using Satellite Data Assimilation*
Maslanik, James	University of Colorado	*Improving the Simulation of Sea Ice Lead Conditions and Turbulent Fluxes Using RGPS Products and Merged RADARSAT, AVHRR and MODIS Data*
Meier, Walter	NOAA (currently at the Naval Academy)	*A Study of the Arctic Halocline Layer using RADARSAT RGPS and AVHRR Products within a Model Assimilation Framework*
Menemenlis, Dimitris	Jet Propulsion Laboratory	*A Global Synthesis of Sea-Ice and Ocean Data for Studying Ice/Ocean Interactions*
Stoessel, Achim	Texas A&M University	*Assimilating Satellite-Derived Sea-Ice Concentration in a Global Coupled Sea-Ice Ocean GCM*
Rothrock, D.A	University of Washington	*Polar Ocean Processes*

As these projects are now well underway, NASA considered it timely to sponsor a workshop to review the individual projects, to reconsider and refine the recommendations from the NSIDC meeting, and to add any new recommendations that would enhance the productivity of this area of research in addressing NASA's science questions. It is the purpose of this document to outline the findings from the workshop and to present the consensus recommendations to NASA on how to make best use of DA as a tool for the sea ice research community.

3 Issues and strategies for DA in Polar Regions

It is clear from the diversity of DA projects that are funded by NASA, and from the potential broad application of DA techniques to the range of science questions that may be addressed with DA, that it would be inappropriate to be over-prescriptive about which DA techniques or applications should be prioritized, although some guidance can be provided in terms of the most pressing scientific questions. Instead, in this document we propose in the main to review some of the key *generic* issues that affect the application of DA techniques to sea ice research.

A key point to make in terms of formulating a strategy for sea ice DA is that the technique will not compensate for a very poor basic model, therefore the basic requirements for good modeling projects apply to DA too.

In general, the following procedure may be considered to apply to projects involving DA.

(a) Formulating the science questions to be answered,

(b) Preparation for assimilation

- ➢ Selecting and constructing a model and DA methods and determining their error characteristics,
- ➢ Selecting forcing and assimilation data and determining their errors,

(c) Performing model simulations with DA, and

(d) Evaluating the model results with respect to the questions posed.

3.1 Formulating the science questions

It is important to stress that we do not advocate DA as an end in itself. Therefore, projects need to be based on science questions that need answering and can be related to the science questions posed by NASA’s ESE. In Table 2 we have attempted to list the science questions that relate to sea ice and have indicated the potential role of DA for each of these questions.

Table 2. NASA Earth Science Enterprise science questions re-framed for sea ice (based on NRC report "Enhancing NASA's Contribution to Polar Science", 2001). In column 3, each PI mentioned in Table 1 is listed (once) under a particular question to provide an indication of where current effort is focused.

Primary Question	Secondary Question	DA area (focus of current NASA-funded PIs)
1. How are the polar oceans changing?	1a. Are changes occurring in the thickness, coverage and circulation of sea ice?	Ice/ocean model DA
	1b. Are changes in high latitude precipitation and surface runoff influencing the Arctic Ocean's salinity, sea ice, and circulation structure?	Ice/ocean model DA
	1c. Is an acceleration of the polar hydrologic cycle apparent in changes in polar precipitation rates over the polar oceans?	Atmospheric DA
	1d. Is the radiation balance changing at the surface of the polar oceans?	Atmospheric DA with forward modeling of satellite-based radiances
2. What are the responses to forcings?	2a. How do the polar oceans respond to and affect global ocean circulation, including consideration of freshwater inputs and export (e.g. rivers, terrestrial ice masses) and relationships to modes of atmospheric variability?	Ice/ocean model DA (Holland, Meier)
	2b. How will albedo-temperature feedback amplify future climate change, including consideration of polar clouds and aerosols, the physical characteristics of melting snow and ice?	Prediction is not helped by DA except in improving and validating the models and in establishing the initial conditions
	2c. Are changes in sea ice cover affecting the amount of atmospheric water vapor?	Atmospheric DA
	2d. How do atmospheric boundary layer processes influence exchanges of heat and freshwater between the cryosphere and atmosphere?	Atmospheric DA
	2e. What role does the cryosphere play in determining the dependence of large-scale atmospheric circulation on the global meridional temperature gradient?	Atmospheric DA
3. What are the consequences of changes?	3a. How will human activities and ecosystems be influenced by consequential changes in the marginal regions of sea ice cover, including economic activity, fishing and coastal defenses?	None
4. Predicting changes in the polar regions	4a. To what extent can transient climate variations in the polar regions be understood and predicted?	Atmospheric DA
	4b. For the purposes of data assimilation by atmospheric and ice/ocean models including numerical weather prediction models, is there a need for new or improved observations from the polar oceans?	Atmospheric DA Ice/ocean model DA (Stoessel)

	4c. What specific improvements to formulations of sea ice and related processes are necessary for accurate simulation and prediction of climate and climate change?	Atmospheric DA (Arbetter, Liu, Zhang, Menemenlis, Lindsay, Markus, Kwok, Maslanik)

The main focus of interest among NASA's sea ice research community lies in the state of the sea-ice cover in terms of its mass balance and its linkage to the energy and freshwater balance. This reflects the focus on the first and second questions above and this is where the priority should lie in the short to medium term. The advent of now mature ice drift datasets, extending back to the late 1970s, has the potential to hugely increase our knowledge of the role of ice dynamics and DA can play an important role in making effective use of these data. Furthermore, data assimilation has potential with regard to the understanding ice thickness changes from the last 20 years or more. Ice thickness is the missing link between ice concentration and drift and ice mass balance, forming the basis for a comprehensive picture of Arctic sea ice processes required to answer Question 1a in Table 1. It can deal with the sparse observations, including possible observations from ICESAT and CRYOSAT, while at the same time constraining estimates of ice thickness using ice concentration and drift and model physics. There is perhaps further to go in making use of sea ice DA in the Southern Hemisphere, given less data in this region, but the potential benefit is just as great.

Moving beyond the confines of sea ice itself, sea ice DA can, of course, help to improve modeling of polar oceanographic and atmospheric processes by improved constrain of the ocean-atmosphere interface. Interdisciplinary activities may be useful to take advantage of this.

3.2 Assimilation Planning

In formulating a strategy, it is worth recalling that, loosely speaking, 80% of the effort in successful implementation and use of DA applies in the work carried out *before* implementation – in preparation of the data, understanding of the errors, trade-offs between technique sophistication and the quality of the input data, etc. As a result, it is all too easy for projects to apply DA techniques prematurely and without adequate information from data providers.

In general, for DA the human and computational resources required is high relative to the average research project, particularly in the case of a new DA initiative. There is always inadequate knowledge about error statistics for model outputs, or about model physics. Models are invariably biased to some extent. Furthermore, ancillary model tools, such as tangent-linear and adjoint models, are also often required for DA. Typically, these software technologies are not readily available. It also raises issues related to the selection and funding of projects.

With finite resources, the relatively high investment required for DA suggests fewer, larger projects, or the implementation of cross-project collaborations that can, for example, involve sharing of DA code. Kalman Filter and variational DA methods are particularly computationally demanding. There may be some efficiencies that can be planned here in the organization of projects that would minimize the requirement for more resources. A similar question applies to the development of adjoint sea-ice models. Building and setting up a fully operational adjoint model puts a heavy burden on limited resources. There are only a handful of adjoint models in operation even in the ocean and atmosphere research communities. Most of these have been set up for operational forecasting and not for research. This begs consideration of the extent to which the community should be encouraged to develop DA capabilities through standard science-based research announcements, or whether one or more specific DA efforts should be explicitly called for. This issue remains an open question.

Beyond the resource and training issue, careful preparation must be made in all three areas of models, methods and data. Many of the DA strategic issues on data were covered at the previous sea ice DA meeting (Weaver et al., 2000) and we do not intend to present all of the details, for which there are a number of good references. See for example the text by Wunsch (1996) or the set of papers found in Ghil et al (1997), plus the National Research Council report (1991) and Anderson et al., (1996) paper. An excellent set of notes from a lecture series is found at the European Center for Medium Range Forecasting (wms.ecmwf.int/newsevents/training/rcourse_notes).

3.2.1 Forcing and Assimilation data

Forcing data are time-dependent variables within the model that are introduced from outside the model without modification. Although the information in forcing data is incorporated into the model, commonly we say that assimilation data are used to modify prognostic variables with additional procedures that are not part of the basic model. Typically the model state is used to estimate the value of a parameter at the time and location the observation was made and the model-based estimate is compared to the observation. Prognostic variables within the model are then modified based on the difference between the model-based estimates and the observations. Important issues to consider for selecting the forcing and assimilation data are errors, biases, irregular temporal or spatial sampling, model times not matching observation times, and changing mixes of available data.

Table 3. Arctic Variables and their uses for Data Assimilation

Variable	**Sources**	**Comments**	**Assimilation Prospects**	
Profiles of atmospheric temperature and humidity	Radiosondes, TOVS	TOVS profiles are under utilized	TOVS profiles could be used more extensively in atmosphe reanalysis efforts	
Ice motion	Buoys, manned stations, SSMI, AVHRR, RGPS	This is the most developed assimilation variable in ice/ocean models. Highly variable error characteristics	Optimal Interpolation works well if enough observations a available	
Ice deformation	RGPS, SSMI	Accurate deformation estimates might be directly assimilated into a model or used as forcing variables	Setting and finding appropria temporal and spatial scales ar key	
Ice concentration	SSMI, historical ice charts	Both sources observe ice extent most accurately. SSMI ice concentration in the interior of the pack not useful.	Modified nudging procedures emphasize ice extent informa	
Mean Ice Thickness	Submarines, moored ULS	Very sparse	Potentially very important. Perhaps best used for model validation and tuning	
Ice surface temperature	IABP/POLES, AVHRR, TOVS			
Surface winds, P-E, surface radiation fluxes, surface turbulent fluxes	Re-analyses	Accuracy uncertain		
Thickness distribution	Submarines, moored ULS	Used for model validation.	"	
Lead fraction, including refrozen leads	AVHRR	It could be a good validation data set for thickness distribution models	"	
Lead orientation	AVHRR, SAR	Model validation for anisotropic rheology models.	"	
Snow depth	We need one	This is a critical variable, perhaps causing the greatest uncertainty in model albedo and growth-rate calculations		
Ocean temperature	Moorings, Salargos buoys	Little used for assimilation	Model validat tuning.	Constrain of ocean circulat models
Ocean salinity	"	"		
Ocean currents	Moorings only	"		
Sea surface temperature	AVHRR	Ocean only		
Sea surface height	Altimeter	Mainly ocean, possibly in ice models		

Some DA methods can also be used to interpolate or smooth observations to a grid or to merge observations from different sources (data fusion) in order to make them more amenable for use as forcing data, assimilation data or validation data. A very extensive data assimilation effort is the NCAR/NCEP Reanalysis, which uses a global atmospheric model to assimilate a myriad of atmospheric observations. The results of that data assimilation effort are often used as forcing variables for Arctic ice and ocean models. Ocean variables may eventually be used in a similar way. Global models which assimilate ocean data from many places and sources would provide time-varying boundary conditions for high resolution regional ice/ocean models. Table 3 lists a number of Arctic ice, ocean, or atmospheric variables and their use as forcing or for assimilation.

It cannot be emphasized enough that understanding quantitatively the errors in the data is essential for successful DA efforts. Errors include instrument errors, algorithm errors, and sampling errors. These last arise from mismatches between the model temporal and spatial resolution, the measurement temporal and spatial averaging, and the temporal and spatial scales of variability in the observed parameter. For example if the measurement is a point value of a variable with small spatial scales of variability and the model has a large grid size, a sampling error may result (also called representativeness error). NASA should maintain effective communication between the accuracy requirements of the models and those available from data sources as a means of guiding where the focus efforts in improving data products.

3.2.2 Model selection and DA methods

The most common sea ice models are Eulerian coupled ice/ocean models with a variety of thermodynamic growth formulations and ice rheologies. A discreet element model and a Lagrangian model are also being developed. A challenge to any modeler is to keep the model as simple as possible, yet include all the important physical mechanisms.

Consideration should be made to ways in which to estimate the growth of model errors. Both optimal interpolation and Kalman filtering methods depend on estimates of the model error, an error that is likely variable in time and space. Model results are most useful when accompanied by estimates of the errors. An important issue for data assimilation is the possibility of formulating an adjoint model. Some model operations, such as discontinuous switches, are particularly difficult, if not impossible, to convert to an adjoint model.

There are a wide variety of DA methodologies available for the practitioner of the art. It is not the purpose of this report to review all of the DA techniques but Table 4 lists some of the more common DA methodologies and some of the applications in Arctic ice/ocean models. The most basic form of data assimilation is the tuning of a model to remove biases (zeroeth order DA). In this procedure, model parameters such as drag coefficients or exchange coefficients that are poorly known are adjusted to minimize a cost function, often the RMS difference between the observations and the model-based estimates of the observations. The tuning may change if any aspect of the model, such as a physical parameterization, resolution, or forcing variables, are changed. For example, the IABP geostrophic winds are significantly slower than those from the NCEP Reanalysis, so the appropriate drag coefficients may be larger. Although tuning is the most basic DA application, it is likely the most important, since the other time-dependent methods require an unbiased model to work well. The tuning of the models should be well documented and routine. A method based on Green's Functions was discussed at the workshop. The adjoint method is also well equipped to accomplish model tuning.

Forward modeling is a method in which the model state is used to estimate the radiances that would be observed by a satellite. These radiances can then be compared to the actual observations, a comparison that can be used to either determine the revised model state, or to enter in a cost function for an adjoint model. Forward modeling may find a role in the future, but is not used yet in applications. This does however suggest that it is important for algorithm developers (mission science teams, and data centers) to ensure that the forward models implicit in inverse algorithms are published and referenced.

3.3 Evaluating the model results with respect to the questions posed

Evaluation is clearly a key step and demands careful thought. Withholding of data is one method to evaluate the results, others involve assessing internal consistency (ability of the model to conserve physics) and perhaps operational issues related to efficiency of running the model in DA mode. Another method is to use synthetic data twin experiments to evaluate the method and the model. Self-consistency of the results can be assessed using a sequential method like nudging, optimal interpolation, or a Kalman Filter. With these methods the assimilation procedure may cause imbalances in some of the prognostic equations and may violate the conservation of some conserved quantities. For example the momentum balance may not be maintained or the ice mass may not be conserved. With the adjoint method the results are exact solutions to the model equations and are therefore consistent, therefore some of these assessment criteria are built into the DA procedure showing why the adjoint method is attractive. With any DA scheme, it is important that the non-linearity of sea ice is retained without damaging its long recognized plastic behavior.

It is worth pointing out that, in some cases, DA can result in aspects of the model behavior becoming worse, suggesting that the model may have originally been generating reasonable results (in some aspects) for the wrong reasons, and hence pointing to the need for some re-evaluation of the physics. In these cases, although the results may be disturbing, they are important to detect and can potentially lead to a major insight into poor behavior within the model, which was otherwise not obvious because the model was erroneously approximating reality.

A further valuable role that the sea ice DA community can play is to provide guidance for specification of future data-sets. The evaluation of DA results can help to pinpoint the circumstances under which large model errors remain – geographically or at particular temporal sampling, for example.

Table 4. Some Methods of Data Assimilation

Method	Description	Arctic Applications	Pros	cons
Replacement	Model values replaced with observations	Ice extent	Very simple	Ignores known errors in the data or model. May produce results inconsistent with model-based physics.
Nudging	Blends observations or climatolo $x = x_f + K(y-Mx_f)$, where xf is the first guess of the model state. The size of K is related to the time constant of the nudging. It can also be related to the difference $(y-Mx_f)$	Ocean temperature or salinity, ice concentration	K can be adjusted to reflect the confidence in the observations and model. A small value of K gives small weight to the observations (long time constant).	See above.
Green's Functions	A method of tuning a model by minimizing a cost function through the performance of a series of sensitivity studies.	Has been used to tune many parameters in a coupled model.	Tunes a model in a systematic, documented, and repeatable procedure to minimize bias.	Requires many simulations to be performed.
Optimal Interpolation	Interpolates the observations and model values by determining the optimal value of K based on the error covariances of both the observations and the model.	Ice velocity, air pressure, air temperature.	Easy implementation. Accounts for model and observational error covariances and the spatial structure of these covariances.	The results are sensitive to the error covariance of the model and observations, so these need to be known accurately.
Kalman Filter	Combines the model prediction and the observations to minimize the estimation error.	Altimeter data, thickness distributions	The model errors are computed from the model dynamics.	Can be computationally expensive.
Kalman Smoother	Uses both past and future observations to minimize the estimation error.	?	See above	See above
Adjoint Models	An adjoint model is constructed in order to determine the best model parameters needed to minimize a cost function.	Non yet, but there may be soon.	The solutions obtained are exact solutions to the model equations (strong constraint) and the model errors are estimated. The method can be used to estimate the both the best initial conditions and the best model parameters	

4 Recommendations

Science questions

- NASA should ensure that the sea ice community generates a consensus view on any unique role of DA in addressing NASA's science questions and ensure that the key questions are publicized among the research community. A starting point is provided in this document.
- NASA should ensure that the community regularly updates its estimates of required accuracies of parameters to address the science questions, and that investigators are aware of where these NASA-approved estimates can be found. These can be used to guide the practitioners of DA.

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- NASA should support the availability of a web-based or other tutorial for data assimilation aimed not at fellow experts in the field, but at scientists and graduate students who would like to become proficient practitioners of the art. A summer school in DA would also be of benefit to encourage a new generation of expertise in DA among the sea ice community.

Models and DA methods

- Model tuning as a "zeroth" order DA activity should be routinely carried out by modelers. The tuning should be systematic, documented, and repeatable since it can change if any of the model parameterizations or the forcing functions are changed. Strategies for the use of DA in model tuning need to be considered carefully, possibly within the framework of coordinated model tuning activities using similar domains.
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- NASA should support a very simple sea ice adjoint model so that we can gain experience in this type of model. The strategy here is to start simple rather than to attempt to construct an adjoint model from a fully complex thickness-distribution model. This should be complementary to other supported studies that are based on simpler DA methods such as Optimal Interpolation, which has been found to be effective in improving the calculation of both ice motion and thickness.

Selecting forcing and assimilation data

- Encourage data providers to characterize the error covariance of both forcing and assimilation data. It is important to understand any covariability in the errors, since the errors are often not independent and the covariance is needed for proper data assimilation.
- Encourage modelers to
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    - specify data formats that are most useful.
- NASA should support development of improved data products, including:

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    - ice thickness.
    - a single archive of ice thickness measurements from submarines and moorings.
    - better characterization of the errors in SSMI-based ice concentration estimates.
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- NASA should consider support of studies that test assimilation scenarios involving pre-satellite era sea ice data as well as post-satellite era sea ice data.

Assimilation stage

- NASA should make available to individual investigators computational resources that could be accessed quickly for short time periods, say six months, until more long-term support could be obtained. The resources should include access to popular modeling environments, such as Matlab® or IDL®, and sufficient disk space to keep large model outputs. Community-wide DA programs should also be considered as a means of obtaining good return on investment in DA.

Evaluation stage

- DA investigators should clearly establish whether their accuracies are most limited by the DA method, the data or the model, or some combination.
- All studies should go beyond quantitative evaluation of the results of DA and should consider the implications for future observation requirements as well as model improvements.

5 Metrics to assess progress in DA applied to sea ice

Metrics are a collection of key statements against which the extent of general progress in sea ice DA can be assessed. They are useful for NASA as a means of assessing, in a program management as well as technical sense, the level of success of a particular activity such as DA. Thus far some of the key issues in different stages of sea ice DA, which we are facing now and will likely face in the future, have been described. These issues can also be used to help specify metrics. The following list is by no means exhaustive or hierarchical. Nonetheless a sense of priorities is built with an underlying goal of building necessary infrastructure and a critical mass for possible community-wide activities in the future.

By Project:

(e) Does the project clearly address one or more science questions?
(f) Does the project address a temporal and spatial domain appropriate for the science questions, and does the project select parameters, establish error requirements and prepare a model and method all in a self-consistent manner? Mismatch between the DA method, the science questions being addressed, and the knowledge of errors in the data, for example, needs to be avoided.
(g) Does the project result in a quantitative evaluation of the results of DA?
(h) Does the project result in recommendations to NASA relating to datasets and model improvements?

By Community:

(e) Has the sea ice community identified a set of specific science questions that are particularly geared toward and/or suitable for DA? Has the particular role of DA in answering NASA's Earth Science Enterprise science questions been established?
(f) Are there any significant gaps in the current range of science questions being addressed with DA, based on those questions identified as being most appropriate for DA in (a)?
(g) Has a consensus methodology been established for evaluating the results of DA?
(h) Does the sea ice DA community have the combined expertise and means of communication to build up the critical mass necessary to carry out an effective program of DA for sea ice, in particular to address activities such as a development of a community adjoint model or broadly-accepted recommendations on data acquisition?

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7 Appendix A: Meeting Agenda

Sea Ice Data Assimilation Workshop

Annapolis, July 23-24 2002

Day 1

1. NASA perspective on workshop and program	Abdalati	8:30-8:45
2. Objectives of workshop	Partington and Ukita	8:45-8:55
3. Local arrangements	Meier	8:55-9:00

4. Summary of activities

- Objectives of the project
- Why DA is required in this project?
- What has been achieved so far?
- What are main technical challenges?
- What are other challenges (data availability, instrument error knowledge, etc.)
- What are the goals for this next 12 months?

Lindsay (UW)	9:00-9:45
Fowler (Colorado)	9:45-10:30
Break	
Ukita (GSFC)	10:45-11:30
Discussion	11:30-11:45
Lunch	
Arbetter (Colorado)	1:00-1:45
Zhang (UW)	1:45-2:30
Discussion	2:30-2:45
Break	
Markus (GSFC)	3:00-3:45
Menemenlis (JPL)	3:45-4:30
Holland (NYU)	4:30-5:15
Discussion	5:15-5:45

Day 2

5. Perspectives from other communities

Haine (Johns Hopkins)		8:30-9:15
O'Connors (NIC) and Carrieres (CIS)		9:15-10:00
Break		
Proshutinsky (WHOI)		10:15:10:45
Francis (Rutgers)		10:45-11:15
Kwok (JPL)		11:15-11:45
Discussion		
Lunch		
6. Data assimilation metrics	Ukita	1:00-2:00
7. Main technical challenges	Lindsay	2:00-3:00
8. Recommendations to the agency	Partington	3:00-4:00
9. Closing	All	4:00-4:10

6. Data assimilation metrics — Ukita — 1:00-2:00

- What can we accomplish through sea ice DA?
- How do we know whether it is working well?
- What is the strategy for sea ice DA?

7. Main technical challenges — Lindsay — 2:00-3:00

- Methods
- Models
- Data requirement

8. Recommendations to the agency — Partington — 3:00-4:00

- Validation activity
- Project cross-cooperation
- Instrument designs (e.g. for sensor error characterization)
- Technical tasks not covered by existing plans
- Future satellite missions
- Cooperation with the operational community and other agencies

9. Closing — All — 4:00-4:10

- Writing assignment (a report due Sep)
- Future plan

8 Appendix B: List of Participants

Waleed Abdalati	NASA HQ	wabdalat@hq.nasa.gov
Todd Arbetter	CIRES/U. Colorado	arbetter@cires.colorado.edu
Cheryl Bertoia	NIC	chryl.bertoia@noaa.gov
Tom Carrieres	CIS	Tom.Carrieres@ec.gc.ca
Stephen Cohn (absentee)	GSFC-DAO	cohn@dao.gsfc.nasa.gov
Charles Fowler	U. Colorado	cfowler@colorado.edu
Jennifer Francis	Rutgers	francis@imcs.rutgers.edu
Ron Kwok	JPL	ron.kwok@jpl.nasa.gov
Thomas Haine	Johns Hopkins	twnh@stommel.eps.jhu.edu
David Holland	NYU	holland@cims.nyu.edu
Ronald Lindsay	UW-PSC	lindsay@apl.washington.edu
Thorsten Markus	NASA-GSFC	thorsten@beaufort.gsfc.nasa.gov
Walter Meier	Naval Academy	meier@usna.edu
Dimitris Menemenlis	JPL	menemenlis@pacific.jpl.nasa.gov
Chris O’Connors	NIC	oconnorsc@natice.noaa.gov
Kim Partington	Vexcel UK	partington@vexcel.com
Donald Perovich	CRREL	perovich@crrel.usace.army.mil
Andrey Proshutinsky	WHOI	aproshutinsky@whoi.edu
Jinro Ukita	NASA-GSFC	jukita@fram.gsfc.nasa.gov
Jinlun Zhang	UW	zhang@apl.washington.edu
Yunhe Zhao	NASA-GSFC	yunhe@neptune.gsfc.nasa.gov

9 Appendix C: Abstracts of Workshop Presentations

9.1 Investigation of the assimilation of ice motion in sea ice models:

(NASA Grant NAG5-10556)

Todd Arbetter, CIRES/University of Colorado, Boulder, Colorado

Historically, thetreatment of sea ice in general circulation models has been, at best, based upon a relatively simple constitutive law describing a linear or elliptical rheology. These rheologies were developed 20 years ago and are based on a very limited amount of observations of ice motion, primarily from drift buoys. Nevertheless, modeled fields of ice area, ice extent, and ice volume using these dynamic parameterazations compare favorably with observations. Moreover, the large-scale ice drift pattern agrees with that seen in the drift buoy record.

More recently, however, techniques have been developed which allow sea ice motion to be obtained from the satellite record. While the errors in ice motion are larger than those achieved with buoy measurements, these data represent a substantial increase in the temporal and spatial coverage of sea ice motion observations in both polar regions. Furthermore, the use of data assimilation techniques (in this case optimal interpolation) allows for much-improved hindcasting of sea ice motion. This has implications for other modeled fields. Moreover, the much-increased inventory of observations combined with sensitivity studies can shed insight into deficiencies in the assumptions of a constitutive law (rheology) as well as shortcomings in other parts of the model.

Here, we perform sensitivity studies using linear, elliptical, and free drift constitutive laws, to determine how the models respond to data assimilation, and what effects are seen in the results. Starting with identical initial conditions (Jan 1, 1997) and using identical forcing, the only differences in the cases are the rheology (viscous-plastic, cavitating fluid, linear free drift, linear free drift with stoppage) and whether or not data assimilation of observed ice motion is used. Model runs are performed for two consecutive years (1997 and 1998). The IABP-POLES sea ice model forcing dataset is used.

The modeled ice area fraction for the Arctic basin (100% = fully ice-covered) without assimilation are shown in figure 1a. There is disagreement between the cases as to the breakup of the ice pack (the linear drfit cases begin earlier than the other cases) and the minimum ice coverage (with the linear drift cases prediciting less ice cover). With assimilation (figure 1b), the differences in the cases are much less. As seen in figure 1c, all rheologies overpredict ice drift (for this particular set of forcing data) compared to observations. The effect on predicted ice volume (figure 1d) is variability in volume depending on season and rheology.

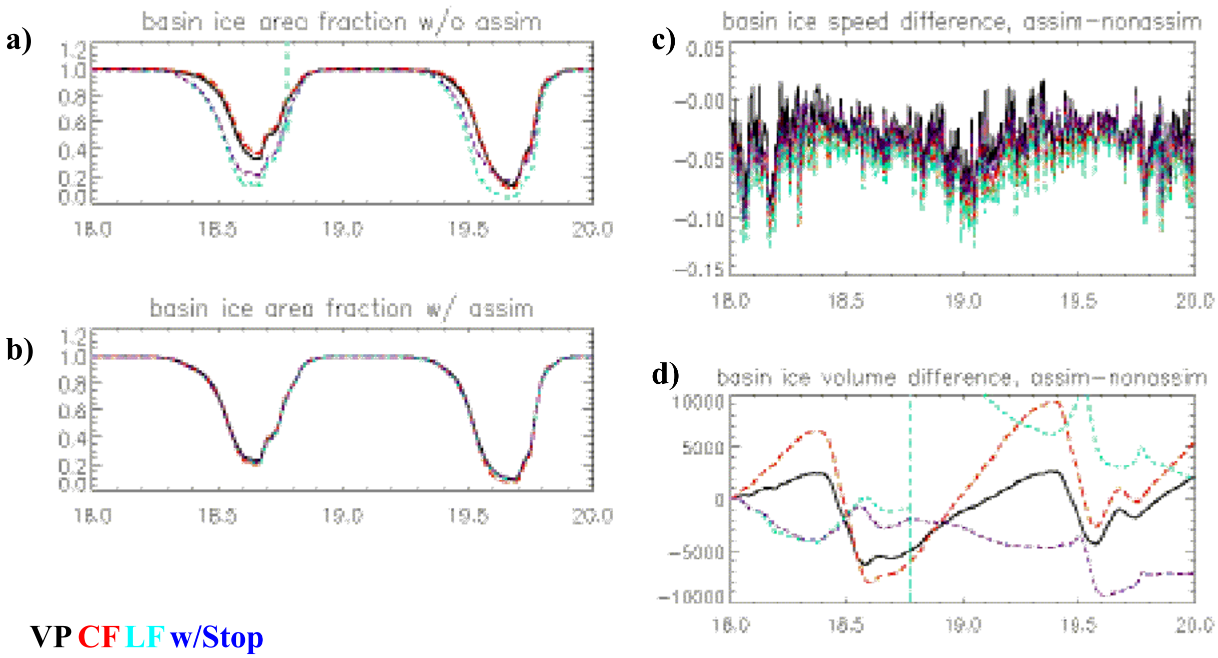


Figure 1: (a) fraction of ice-covered area/total area for the Arctic basin for model cases without data assimilation; (b) fraction of ice-covered area/total area for the Arctic basin for model cases with data assimilation; (c) difference between mean ice motion, assimilated case minus unassimilated case; (d) difference between total ice volume, assimilated case minus unassimilated case.

Further studies involved using a model containing more sophisticated thermodynamics to investigate how data assimilation affects the ability to hindcast particular sea ice anomalies.

In both cases, data assimilation provides a dramatic effect not only on the ice motion but on other modeled fields. The results indicate that a change in the ice motion fields has a direct and cumulative effect on other model properties. Moreover, removing the variability in the forcing sheds light on deficiencies in other parts of the model. In the results shown here, the modeled ice area is consistently too low, but because the sea ice motion variability has been removed, we can look to other model components (e.g., forcing) for methods of improvement.

9.2 Observations of the Arctic Atmosphere for Assimilation by and Validation of Models: New Data Sets, New Problems, and New Solutions

Jennifer Francis
Institute of Marine and Coastal Sciences
Rutgers University, New Jersey

This presentation described several new satellite-derived data sets for the Arctic basin that may be valuable for validating models, developing new parameterization schemes, and for direct assimilation. Products are retrieved at daily temporal and (100 km)2 spatial resolution for 20 years between 1979 and 1998 from radiances observed by the TIROS Operational Vertical Sounder (TOVS) [Francis and Schweiger, 2000; Schweiger et al, in press]. Products of potential interest to the Arctic sea ice modeling community include near-all-weather surface skin temperature, cloud cover, geostrophic drag coefficient and turning angle, net precipitation, surface longwave radiation, and horizontal atmospheric heat advection. Extensive validation has been performed using data from SHEBA, CEAREX, LeadEx, Russian NP stations, and COADS.
Recent efforts to validate a variety of Arctic data sets have revealed problems that will require further efforts to resolve. These include large biases in upper-level winds from reanalyses [Francis, in press], inter-satellite biases in TOVS radiances, regionally and seasonally dependent errors in surface-observed air temperatures [Chen et al, in press], and shortcomings in Arctic applications of global surface radiation flux algorithms [Chiacchio et al, 2002]. In response to these recently discovered problems, several efforts to find solutions are underway. These projects were briefly described.

9.3 An Impact of Subgrid-Scale Ice-Ocean Dynamics on Sea-Ice Cover

David Holland

New York University

A coupled sea-ice-ocean numerical model is used to study the impact of an ill-resolved subgrid-scale sea-ice-ocean dynamical process on the areal coverage of the sea-ice field. The process of interest is the transmission of stress from the ocean into the sea-ice cover and its subsequent interaction with the sea-ice internal stress field. An idealized experiment is performed to highlight the difference in evolution of the sea-ice cover in the circumstance of a relatively coarse-resolution grid versus that of a fine-resolution one. The experiment shows that the ubiquitous presence of instabilities in the near-surface ocean flow field as seen on a fine-resolution grid effectively leads to a sink of sea-ice areal coverage that does not occur when such flow instabilities are absent, as on a coarse-resolution grid. This result also implies that a fine-resolution grid may have a more efficient atmosphere-sea-ice-ocean thermodynamic exchange than a coarse one. This sink of sea-ice areal coverage arises because the sea-ice undergoes sporadic, irreversible plastic failure on a fine-resolution grid that, by contrast, does not occur on a coarse-resolution grid. This demonstrates yet again that coarse-resolution coupled climate models are not reaching fine enough resolution in the polar regions of the world ocean to claim that their numerical solutions have reached convergence.

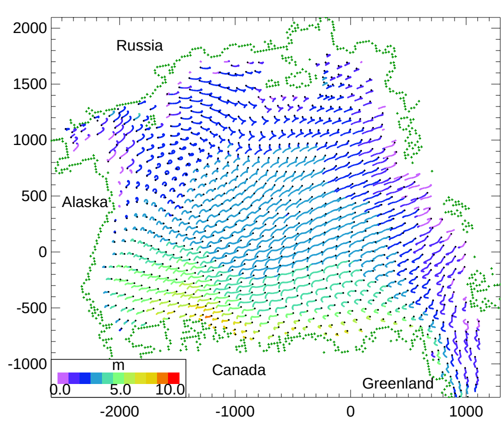
9.4 A Lagrangian Dynamic Model of Sea Ice for Data Assimilation

R. W. Lindsay
Polar Science Center, University of Washington, Seattle WA

A new Lagrangian dynamic model of sea ice for the Arctic Basin was presented. The model consists of Lagrangian cells, each defined by its position and the velocity, mean thickness, and compactness of the ice. The cells are considered to be representative of a smoothly varying field of these last three variables but do not have a conserved area. The initial spacing of the cells is on a 100-km grid. The time evolution of the position and velocity of the cells is found by integrating the acceleration equation which includes terms for the Coriolis force, wind stress, water stress, and internal ice stress. The internal ice stress is computed from a viscous plastic ice rheology in which the strain rate is determined using the Smoothed Particle Hydrodynamics formalism. This method uses a weighted sum of the velocity of the cells in the vicinity of a point to determine the spatial gradients of the velocity. The integration is performed with an adaptive time stepping procedure. Boundary conditions are imposed in two manners: by assuming the coast is composed of thick, stationary ice and by imposing a $1/r^2$ repulsive force with a short length scale. The coast is defined by points with a 25-km spacing. Thermodynamic ice growth is taken from a seasonally dependent growth-rate table. The model is forced with IABP geostrophic winds for a two year period.

The figure shows the trajectories of the cells for a 10-day period. The colors indicate the ice thickness. The velocity of the cells was compared to daily buoy velocities over the two year period. The correlation is $R = 0.72$ ($N = 12{,}216$) which is comparable to state-of-the-art Eulerian sea ice models. This level of agreement is likely due to the fact that the ice velocity is well correlated with the geostrophic wind and the model is capturing the wind-driven portion of the variance reasonably well.

Some ideas were discussed about assimilation of ice trajectory data from buoys or from RGPS. Two approaches were presented: one is kinematic, in that the trajectories are modified to match the observed trajectories without regard to the force balance equation; a second is dynamic, in that a corrective force is computed that is added to the force balance equation and insures that the integration of the equations of motion produces the correct trajectories. The corrective force may be an important diagnostic of the model or of the forcing fields.



9.5 A Global Synthesis of Sea-Ice and Ocean Data for Studying Climate

Dimitris Menemenlis (JPL) and Jinlun Zhang (UW-PSC)

Our key technical objective is to improve the representation of high-latitude ocean and sea-ice processes within the ECCO (Estimating the Cicrulation and Climate of the Ocean, http://www.ecco-group.org/) consortium's modeling and data assimilation infrastructure. This involves 1) the addition of a dynamic-thermodynamic sea-ice model, 2) the inclusion of the Arctic Ocean, and 3) the derivation of the sea-ice model adjoint. Achieving these technical objectives will make it possible to use the wealth of existing and planned sea-ice data sets in studies of global climate, specifically, in improving estimates and models of the oceanic storage, transport, and air-sea exchange of heat, freshwater, and biogeochemical tracers. We are particularly interested in using the the above tools to study the role of sea-ice and high-latitude processes in the global carbon cycle.

The first technical objective is completed, that is, we have coupled a dynamic-thermodynamic sea-ice model based on Hibler (1979, 1980) to the Marshall et al. (1977) ocean general circulation model. Sea-ice model thermodynamics are represented by a 2-category model that simulates ice thickness and concentration. Snow is simulated as per Zhang et al. (1998). Ice dynamics are represented by a viscous-plastic rheology which is solved using a parallelized version of the alternating-direction-implicit (ADI) method of Zhang and Rothrock (2000). In preliminary tests and calibrations, the coupled sea-ice, ocean model has been used to assimilate SMMR-SSM/I estimates of sea-ice extent, TOPEX/POSEIDON sea-surface height, and hydrographic data using a Green's function approach.

For inclusion of the Arctic Ocean within the ECCO infrastructure, we are experimenting with a cubed-sphere and with a tripolar grid configuration. Development of the sea-ice adjoint model is underway.

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Marshall, J., et al., A finite-volume, incompressible Navier-Stokes model for studies of the ocean on parallel computers. J. Geophys. Res., 102, 5753-5766, 1997.

Zhang, J., et al., Arctic ice-ocean modeling with and without climate restoring. J. Phys. Oceanogr., 191, 191-217, 1998.

Zhang, J., and D. Rothrock, Modeling arctic sea ice with an efficient plastic solution. J. Geophys. Res., 105, 3325-3338, 2000.

9.6 Data Assimilation Requirements and Experiences in the North American Ice Centres

Christopher O'Connors (National Ice Center)
and
Tom Carrieres (Canadian Ice Service)

The Canadian Ice Service runs coupled ice-ocean models in support of its 18-hour per day/7 day a week operation. Accurate, high resolution models and driving forces are essential components. Model initialization and data assimilation are increasingly becoming one of the key thrusts at CIS and in most other national ice services as we strive for greater automation and more consistent analysis and forecast products. CIS staff, in collaboration with other Canadian researchers, have made a number of studies on data assimilation. For ice concentration, it appears that data insertion is superior to simple nudging techniques. It also appears that while assimilation of ice drift may improve ice analyses, it provides little if any benefit to ice forecasts. Also, since ice thermodynamics near the ice edge may be as important as ice drift for even 24-hour forecasts, assimilation of SST must also be considered. This requires high resolution and accurate observations near the ice edge and an assimilation system which adjusts temperatures at depth and also is fully compatible with available ice information. Assimilation of ice concentration and SST will be one of the main efforts of the CIS Applied Science Division for the next several years.

9.7 Representation of Antarctic Coastal Polynyas in Ocean Climate Models: A Justification for Assimilation of Ice Concentration?

Achim Stoessel

Department of Oceanography
Texas A&M University, College Station

Thorsten Markus

NASA Goddard Space Flight Center
Greenbelt, Maryland

Abstract

The representation of Antarctic coastal polynyas in global ocean general circulation models (OGCMs) have a profound impact on long-term deep-ocean properties. Compared to maximum ranges in magnitude of ambient conditions such as wind velocity and air temperature, the extent of coastal polynyas play the most decisive role in determining the rate of Antarctic Bottom Water formation, through the process of sea-ice formation, brine release, and formation of High Salinity Shelf Water. This study investigates the local, regional and high-frequency behaviour of the model representation of coastal polynyas with the aid of daily ice concentration derived from satellite passive microwave data using the "NASA Team 2" algorithm. Large regional and temporal discrepancies arise that are primarily related to the type of convection parameterization used in the model. Arguing that the empirical "thermodynamic lead closing" parameter is the weakest part in the sea-ice component of the OGCM, ice is being redistributed within a model grid cell by assimilating NT2 ice concentration. This measure yields potentially more reliable estimates on the impact of critical high-latitude processes on long-term deep-ocean properties. On the other hand, there are still various issues to be solved, e.g. whether the presented assimilation strategy is useful for the entire ice pack, how to properly deal with coastline mismatch between data and model, and how much assimilation of daily data interferes with daily winds that drive the sea-ice model. Besides the assimilation, this paper has revealed major short-time scale discrepancies between modelled and satellite-derived ice concentration, suggesting that much work is still needed to improve subgrid-scale high-latitude processes in global OGCMs.

9.8 Spatial and Temporal Characteristics of Arctic Sea-ice Deformation and its Implication in Data Assimilation

Jinro Ukita, Antony Liu, and Yunhe Zhao

NASA-Goddard Flight Space Center
Code 971
Greenbelt, MD 20771

On interannual to decadal timescales atmospheric circulation exhibits strong modal structures, in which coherent and recursive patterns such as ones defined by NAO and AO emerge. These modes and their associated phases have Arctic manifestations as evidenced by different modes in ice motion. Given this background questions arise as to how these variations in ice motion lead to varying modes of ice deformation, how these modes in deformation modify the way in which sea ice mass is redistributed, how this is compared to possible influence on the mass balance by other oceanic and thermodynamic processes, e.g. more oceanic heat flux, higher air temperature, or more snow precipitation etc., and how this ultimately modifies the sea ice mass balance and eventually the regional freshwater balance. These questions can be more effectively answered through an optimal use of model outputs and data – data assimilation. The first and important step in this effort is to make a critical assessment on data so as to identify relevant spatial and temporal scales for assimilation analysis.

The process most directly responsible for the redistribution of sea-ice mass is uniaxial closing (contraction), e.g. a ice flow against the coast. Yet it is a rare class of events as on the average Arctic ice motion is close to being non-divergent. This requires a careful analysis on how to extract information characterizing this process. Our results based on merged ice motion data constructed from satellite and buoy observations indicate that the relevant timescale for this process likely falls in the range of month to season. Over this temporal scale the emerged spatial pattern on the frequency of uniaxial-contraction events resembles to observed and simulated patterns in ice thickness. These results suggest that within this framework roughly speaking daily to synoptic timescale is a required temporal resolution for assimilation analysis to be both valid and meaningful. They also suggest an effectiveness of a 100 km resolution.

On the basis of this assessment work is under way to construct a simple forward and adjoint ice dynamic model.

9.9 On the Effect of Data Assimilation on Sea-Ice Simulations

Jinlun Zhang[1], D. R. Thomas[1], D. A. Rothrock[1], R. W. Lindsay[1], Y. Yu[1], and R. Kwok[2]
[1]University of Washington Polar Science Center
[2]California Institute of Technology Jet Propulsion Laboratory

Abstract

Aided by submarine observations of ice thickness for model evaluation, we investigate the effects of assimilating buoy motion data and satellite SSM/I ice motion and concentration data on simulation of Arctic sea ice. The sea-ice model is a thickness and enthalpy distribution model and is coupled to an ocean model. Ice motion data are assimilated by means of optimal interpolation. Ice concentration data are assimilated by a blending scheme. Assimilating motion data, particularly from drifting buoys, significantly improves the modeled ice motion, reducing the error to 0.04 m/s from 0.07 m/s and increasing the correlation with observations to 0.90 from 0.66. Without data assimilation, the modeled ice moves too slowly with excessive stoppage. Assimilation leads to more robust ice motion with substantially reduced stoppage, which in turn leads to strengthened ice outflow at Fram Strait and enhanced ice deformation everywhere.

Enhanced deformation doubles the production of ridged ice to an Arctic Ocean average of 0.77 m/yr, and raises the amount of ridged ice to half the total ice volume per unit area of 2.58 m. Assimilation also significantly alters the spatial distribution of ice mass and brings the modeled ice thickness into better agreement with the thickness observed in four recent submarine cruises, reducing the error to 0.66 m from 0.76 m, and increasing the correlation with observations to 0.71 from 0.45. Buoy data are most effective in reducing model errors because of their small measurement error. SSM/I motion data, because of their more complete spatial coverage, are helpful in regions with few buoys, particularly in coastal areas. Assimilating both SSM/I and buoy motion data combines their individual advantages and brings about the best overall model performance in simulating both ice motion and ice thickness. Assimilating satellite ice concentration data improves ice thickness near ice edge.